TEXAS INSTRUMENTS

TLE2027/TLE2037

Operational Amplifiers

- ***Ultra Low-Noise, 15 MHz — Unity Gain Bandwidth***
- ***Ultra Low THD, 60 MHz — Gain Bandwidth Product***

Design Considerations

1991

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TLE2027/TLE2037

Ultra Low-Noise, 15 MHz — Unity Gain Bandwidth/Ultra Low Total Harmonic Distortion, 60 MHz — Gain Bandwidth Product Operational Amplifiers

TEXAS INSTRUMENTS

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Introduction

The TLE2027 and TLE2037 are recent additions to the ever-growing family of Excalibur Operational Amplifiers from the Linear Products Division of Texas Instruments. This family of single operational amplifiers, soon to be available in dual and quad versions, is the first family offered in the mid-range of frequency performance with bandwidths in the 15-MHz (TLE2027) and 60-MHz (TLE2037) areas.

However, Excalibur operational amplifiers offer much more than speed. Features such as extremely low noise voltage, 2 $nV/\sqrt{Hz}$; excellent total harmonic distortion, 0.001%; near ideal open-loop gain, 160 dB; and ultra-low offset voltage, 25 μV; all wrapped up in either small outline (SOIC) or standard plastic (DIP) packages, make the family useful all-around amplifiers. Audio circuits, filters, and highly accurate instruments can all benefit from the family's superior performance.

This document is divided into the following three sections: technology comparison, design considerations, and application considerations. The first section compares several parametric features of various op amp technologies. These comparisons are made in four specific areas: dc performance, dc errors related to applications, ac performance, and noise performance. The design consideration section focuses specifically on the TLE2027/37 Excalibur family. The total harmonic distortion and output saturation recovery performance features of this family of devices are evaluated in detail. Finally, the third section discusses several application features of the TLE2027/37.

Welcome to the world of Excalibur Technology.

Technology Comparison

DC Performance

Table 1. Device/Technology Comparison of DC Performance

Process	BIPOLAR	EXCALIBUR		BIFET	LinCMOS™		UNITS
DEVICE	µA741	TLE2021B	TLE2027A	TL051A	TLC2201A	TLC2652A	
V_{IO}	6000	100	25	800	200	1	µV
I_{IB}	500	50	90	0.2	0.005	0.01	nA
CMRR	70	100	117	75	90	120	dB
A_{VD}	86	120	140	94	104	135	dB
$\Delta V_{IO}/\Delta °C$	(10)	(2)	1	25	(0.5)	0.03	µV/°C
$\Delta V_{IO}/\Delta t$		(0.006)	(0.006)	(0.04)	0.005	0.06	µV/mo

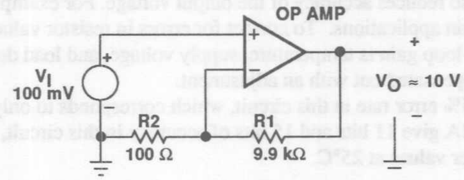
NOTE: All measurements are worst-case values taken at 25 °C, and the (xx) measurements refer to typical values.

Comparing dc error parameter values for different technologies shows that modern bipolar operational amplifiers designed using new processes like Excalibur have a performance far exceeding that of industry-standard bipolar operational amplifiers like the µA741, LM301, and LM324. In the Excalibur technology the offset, its drift, and the input bias current are greatly reduced while at the same time dramatically increasing the open-loop gain. The TLE2021 is designed for low-power precision circuits and the TLE2027 for high-precision circuits that require low noise or high bandwidth. The Excalibur technology improves the op amps' offset stability with time by over 100 times that of similar competitive devices.

BIFET op amps normally have higher input offset voltage and drift compared to bipolar devices. The TL051 represents a second generation BIFET op amp with improved offset and stability over first generation products. Although the input bias currents of BIFET designs are insignificant when compared to their bipolar counterparts, over temperature their bias current doubles every ten degrees. Some bipolar designs actually have lower bias currents at higher temperatures.

Silicon-gate CMOS technologies such as LinCMOS reduce the problem of unstable offsets in MOS designs. The TLC2201, designed using LinCMOS technology, is an example of the new breed of CMOS devices. It offers extremely low and stable offsets while simultaneously featuring the high input impedance and low current noise found in the very best JFET devices. For the ultimate in dc precision, chopper-stabilized op amps such as the TLC2652 provide the absolute lowest input offset and drift at low expense.

DC Errors Related to Application



$$V_O = \left(1 + \frac{R1}{R2}\right) \times \left[V_I + V_{IO} + I_{IB}\left(\frac{R1}{1 + \frac{R1}{R2}}\right) + \frac{V_{CM}}{CMRR} \right] \times \frac{1}{1 + \frac{1}{A_{VD}}\left(1 + \frac{R1}{R2}\right)}$$

DEVICE	µA741	TLE2021	TLE2027A	TL051A	TLC2201A	TLC2652A	UNITS
ERROR	6.550	0.115	0.030	0.998	0.203	0.00388	%
V_{OUT}	9.345	9.989	9.997	9.900	9.973	9.99960	V

Figure 1. Benchmark Test Circuit for Error Comparison

Studying the errors in a simple non-inverting amplifier with a gain of 100 (see Figure 1) demonstrates the importance of careful choice and use of op amps.

With a 100-mV input voltage, the expected output voltage would be 10 V. However, errors from offset voltage, input bias current, finite common-mode rejection ratio, and open-loop gain reduce the accuracy of the output voltage. In a noninverting amplifier, these error terms and the input signal are multiplied by the closed-loop gain (see the equation in Figure 1). However, in an inverting amplifier the error terms and input signal are multiplied by different gains. Therefore, in inverting applications with low-gain circuits, care must be taken because the closed-loop gain can be larger than the signal gain. This can cause significant errors due to the error signals.

As mentioned previously, offset voltage errors can reduce the accuracy of the output voltage. These errors can be adjusted by external trimming. For example, the adjust pins on single op amps can be used to null an op amps' offset. This, however, can increase the temperature drift as the currents in the input stage are brought out of balance. This is more true for bipolar op amps than JFET or CMOS parts. Therefore, the devices' offset adjust pins should not be used to remove other system offsets. Note that improved reliability and reduced trimming cost can be achieved by selecting op amps with initially low offset voltages.

Another type of error that reduces output voltage is related input bias current. The input bias current creates a voltage drop across the parallel combination of R1 and R2, which is added to the offset voltage. When multiplied by the gain, it appears that only the current through R1 contributes to the output error. Therefore, R1 should normally be chosen low such that the error voltage created is lower than the effect of the offset voltage. However, the op amp must also be able to drive the load impedance. This is often a problem in low-gain applications.

As an example, the TLE2021 device is reviewed. The TLE2021 has a maximum input bias current of 50 nA at 25°C. With R1 = 2 kΩ, the bias current contributes as much to the offset as the offset voltage. The error can be greatly reduced by inserting a resistor in series with the noninverting input. By choosing its value to be R1/R2, the bias current error term is reduced to the input offset current (difference in input bias currents of the inverting and noninverting inputs) multiplied by R1. Further note that JFET or CMOS input op amps have very low input bias currents (picoamps) and can be used with very high impedances without introducing significant errors (assuming the temperature range is moderate).

A finite common-mode rejection ratio also reduces the accuracy of the output voltage. The input common-mode voltage in this circuit is 100 mV. Common-mode voltages cause the offset to change with applied input voltage. The error term is expressed by the op amps' common-mode rejection ratio. For example, the TL051A has a CMRR of 75 dB.

Technology Comparison

DC Errors Related to Application

In the voltage-follower mode, with 10 V dc applied to the input, the offset may vary up to 1.8 mV.

Finally, open-loop gain also reduces accuracy of the output voltage. For example, high open-loop gain improves the accuracy of high closed-loop gain applications. To correct for errors in resistor values, a trimmer can be used to adjust the gain precisely. The open-loop gain is temperature, supply voltage, and load dependent; therefore, its error contribution can not simply be compensated out with an adjustment.

The µA741 exhibits a 6.55% error rate in this circuit, which corresponds to only three bits of accuracy. However, the TLE2027A and TLC2652A give 11 bits and 15 bits of accuracy in this circuit, respectively. The calculations are based upon worst-case parameter values at 25°C.

Technology Comparison

AC Performance

Table 2. Device/Technology Comparison of AC Performance

TECHNOLOGY	DEVICE	BANDWIDTH (MHz)	SLEWRATE (V/µs)	SUPPLY CURRENT PER AMP (mA)
BIPOLAR	µA741	1	0.9	1700
	LM324	0.6	0.2	250
EXCALIBUR	TLE2021	2	0.9	200
	TLE2027	15	1.7	3800
	TLE2061	2.1	3.4	280
BIFETS	TL051	3.1	18	2700
	TL031	1.1	2.9	200
LinCMOS	TLC272	1.7	2.9	1000
	TLC27M2	0.5	0.4	105
	TLC27L2	0.14	0.04	15

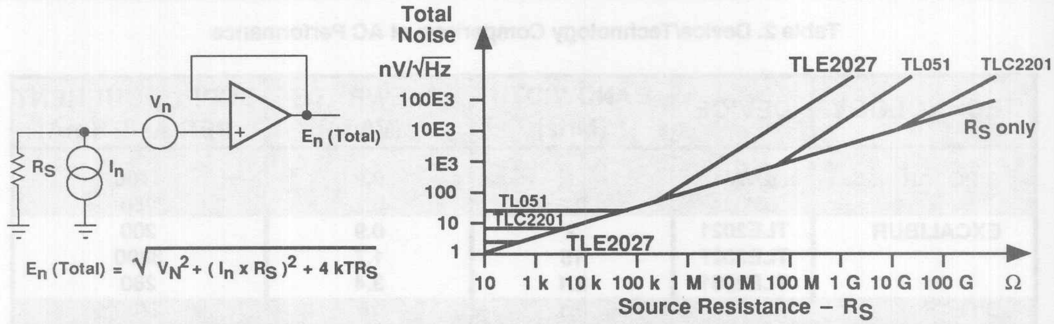
NOTE: All Values are typical.

The table above shows how the performance of a device is dependent upon technology and supply current. Old designs such as the LM324 using very basic IC technologies do not compete with devices such as the TLE2021 that are designed using a complementary bipolar process. The TLE2027 has multiple poles, so although its bandwidth is high, its slew rate is lower than that normally expected. BIFET devices have high slew rates for a particular bandwidth without particularly high supply current, but unfortunately they have poorer and less stable offset voltages.

The TLC27x series of LinCMOS devices highlight how supply current affects ac performance. Each device is essentially the same, but the internal bias currents are altered – each has a different supply current. Other parameters are also changed by this, such as the gain, which is higher for the low bias version. Unlike BIFETs, LinCMOS devices can operate from a single 5-V supply.

Technology Comparison

Noise Performance



Process	BIPOLAR	EXCALIBUR	BIFET	LinCMOS		UNITS
PARAMETER	NE5534	TLE2027	TL051	TLC1078	TLC2201	
Noise Voltage	3.5	2.5	18	68	8	nV/√Hz
Noise Current	400	400	10	0.05	0.06	fA/√Hz
$^1/_f$ Corner	100	3	100	30	50	Hz

Figure 2. Device/Technology Comparison of Noise Performance

Bipolar op amps offer the lowest noise voltage among commercially available op amps. The noise voltage from a bipolar input stage in the flatband is dominated by thermal noise from the base spread resistance and the emitter small signal resistance. The TLE2027 or the decompensated TLE2037 represents such op amps optimized for low noise voltage. The noise current is the shot noise coming from the input's bias current.

Typically, bipolar op amps are best known for low noise voltage. Also, the bipolar inputs yield significant input bias currents. This implies relatively high input noise current. To reduce the bias current and therefore the noise current, superbeta input stages or bias current cancellation circuits are used.

FET input op amps have an input noise current given by the shot noise from the gate current. This is very low at temperatures around 25°C compared to the base current in bipolar inputs. Consequently, FET input op amps have negligible current noise and provide superior noise performance with high impedance sources. However, a FET input stage will have higher noise voltage and also a higher 1/f corner frequency than bipolar.

The noise sources of a MOSFET input device are similar to those of the junction FET. The gate current is negligible and the input current is reduced to leakage currents in the ESD input protection network. A disadvantage to MOSFETs, in general, is their relatively high noise voltage and high 1/f frequency. However, an exception is the advanced LinCMOS TLC2201 op amp. This offers a noise current level similar to the very best FET input op amps and a noise voltage comparable to many bipolar designs. In addition, an offset of only 200 µV max in a plastic package coupled with a very low drift over time and temperature, including rail-to-rail outputs with a single 5-V supply, make this device superior in its class.

Summarizing, bipolar input stages give the lowest noise voltage and lowest 1/f corner frequency and are well suited for interface to low-impedance sources. JFET and CMOS input stages have negligible input current noise allowing them to be used with extremely high source impedances. Note that noise current is related to the input bias current, where bias currents increase by $\sqrt{2}$ for every 10°C temperature rise in bipolar and doubles for every 10°C temperature rise in JFETs. .

Design Considerations

Total Harmonic Distortion Plus Noise Performance

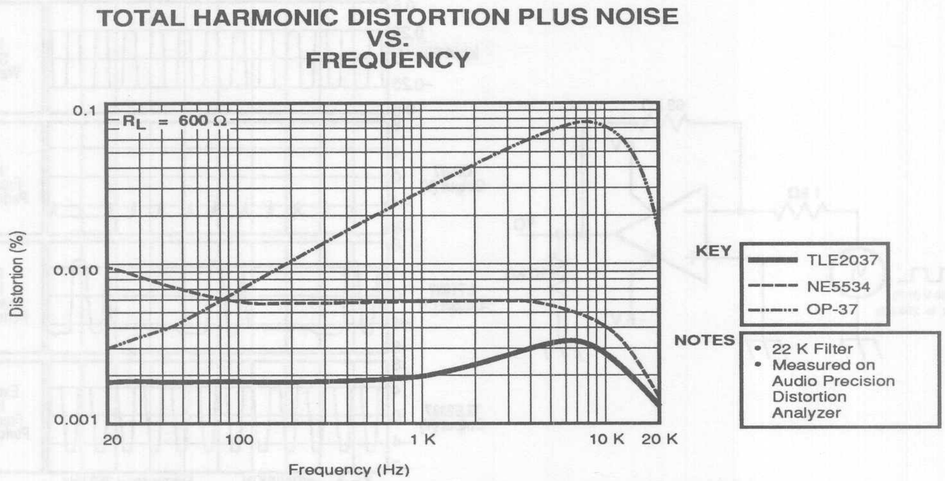


Figure 3. Total Harmonic Distortion Plus Noise Performance

Bipolar amplifiers offer the lowest Total Harmonic Distortion performance among commercially available operational amplifiers. THD is highly dependent upon loop gain, bandwidth, slew rate, crossover distortion, load, and input signal magnitude. The TLE2037 with its advanced process and design technology offers the optimum performance in THD while comprehending all these external/internal parameters.

Audio applications ranging from microphone pre-amps, filters, equalization circuits and output pre-drivers all can benefit from the ultra-low THD output of the TLE2037. Its ability to drive significant loads (600 Ω shown) does not limit it to applications driving high-impedance nodes and allows driving cables as well as multiple paralleled loads.

Notably, slew rate can play a significant role in THD. As the slew rate limit of the device is approached, higher levels of distortion arise until clipping of the output waveform occurs. In the TLE2037, with its relatively high slew rate (considering it is a relatively low power, bipolar operational amplifier), the THD remains significantly below older standard amplifiers as higher frequencies are approached. It is worth noting in Figure 3 that the test system used has an internal 22-kHz filter, which eliminates any high frequency injection into the THD test.

Coupling the excellent low noise input stage of the TLE2027/37 family with its unmatched low THD output stage sets new standards for a wide range of applications in audio and low-to mid-range frequency analog signal processing.

Output Saturation Recovery Performance

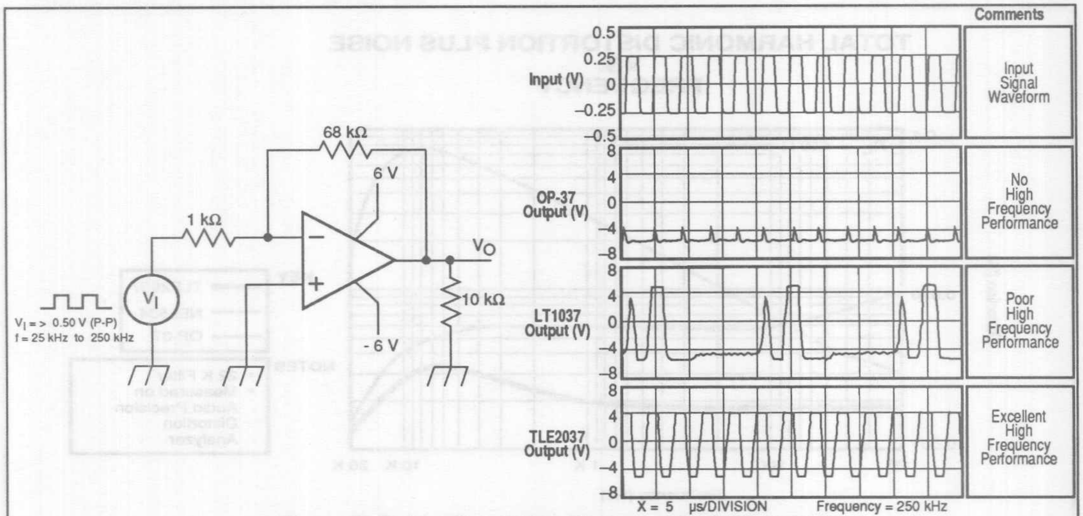


Figure 4. Output Saturation Recovery Performance

In conventional OP-27-type amplifiers, the output voltage remains predictable only if it stays within the V_{OM} specification. If an input signal is applied which tries to force the output voltage beyond the V_{OM} limit, the output may not respond correctly to subsequent input signals until after a given amount of time has passed. This time is the "Output Saturation Recovery Time".

There are three things that can cause the OP-27-type amplifiers to exhibit output saturation recovery problems. First, in some of the amplifiers, the final common emitter gain stage is allowed to be driven heavily into saturation. The excess base charge built up on the device can only be removed via a high value pulldown resistor. Therefore, a finite time must pass before enough charge is removed to assume normal operation.

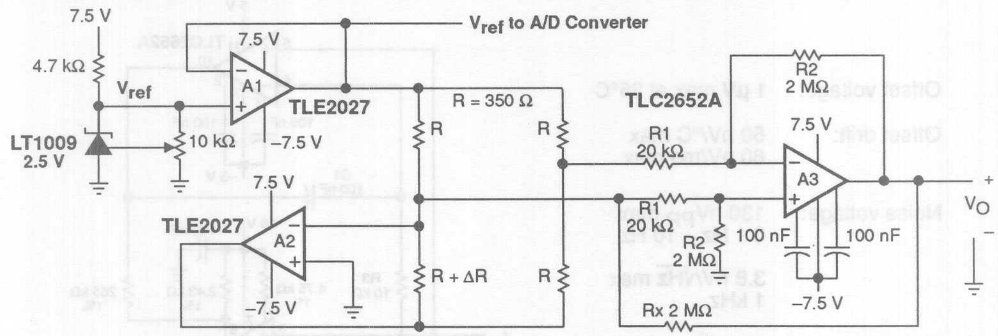
Secondly, the current sources in the class AB output stage are also allowed to saturate. These are not driven as heavily into saturation, but will also take a finite amount of time to recover.

Thirdly, and perhaps most important, the bias generator for the entire circuit can be disturbed from its equilibrium point when the output stage current sources saturate. If disturbed enough, the bias circuit can shut off completely until the start-up circuit engages. If this happens, the entire circuit temporarily loses power and the output signals will not become valid again until the bias generator recovers to its equilibrium state. This results in a huge output saturation recovery time.

In the TLE2027/37, special circuitry has been added to keep the final gain stage and the output stage current sources out of saturation. Therefore, no saturation recovery time is needed and the device continues to operate in a normal, stable, predictable manner.

Application Considerations

Ultra-Linear Strain Gauge Amplifier



Effect of Rx: $V_O = \frac{1}{2}\,\frac{R2}{R1}\,\frac{\Delta R}{R}\,V_{ref}\left(\frac{1}{1-\frac{Ra}{2R1}}\right)$; $Ra = \begin{cases} -R & \text{Without Rx} \\ \Delta R & \text{Using Rx} = R2 \end{cases}$

Effect of V_{IO}: $V_O = \frac{1}{2}\,\frac{R2}{R1}\,\frac{\Delta R}{R}\left[V_{ref} + V_{IO}(A1) + V_{IO}(A2)\right] + \left[1 + \frac{R2}{R1}\right] V_{IO}(A3)$

Figure 5. Ultra-Linear Strain Gauge Amplifier

To minimize errors in accuracy due to the self-heating of the strain gauges, the bridge is powered from a 5-V supply. To reduce power consumption in the op amp's output stage, the TLE2027s are powered from a ± 7.5-V supply.

The excellent dc performance of the TLE2027 reduces errors from these op amps to insignificant values. By using a differential connection of A3, offset errors from A1 and A2 are virtually eliminated. However, the offset error in A3 is multiplied directly with its configured gain.

To keep errors from bias currents low in the x100 amplifier, A3 is a chopper-stabilized amp (TLC2652A). This op amp features negligible bias currents due to its CMOS input structure.

The positive feedback resistor Rx provides an effective Z_{in} of the A3 amplifier stage of more than 1 MΩ, eliminating loading effects of the bridge by the amplifier. Rx should be equal to R2. This resistor reduces the error from approximately 1% to an insignificant level if the variation in the bridge resistance ΔR is small compared with R.

If both sides of the strain gauge are active (two legs compressed and two under tension) or if just one side is active (one leg compressed and one under tension) then, for optimum linearity, the LT1009 band gap reference ground connection should be tied to the output of the op amp A2.

Table 3. TLE2037 and TLC2652 Performance Features

TLE2027 Features		TLC2652 Features	
Low Noise	5 nV/√Hz @ 1 kHz	Ultra Low Offsets	1 µV max (TLC2652A)
High Gain	45 V/µV		3 µV max (TLC2652)
Low Offsets	25 µV max	Low Drift/temp	30 nV/°C max
Wide UGBW	15 MHz typ	Low Drift/time	20 nV/month max
+ Output Saturation Recovery circuit		High Gain	135 dB
		Chopping Frequency	450 Hz typ

Ultra-Low Drift and Ultra-Low Noise Amplifier

Offset voltage:	1 µV max at 25°C
Offset drift:	50 nV/°C max 60 nV/mo max
Noise voltage:	130 nV_{PP} max 0.1 Hz – 10 Hz 3.8 $nV/\sqrt{Hz}$ max 1 kHz
Gain:	$V_O / V_I = 1001$

Gain accuracy limited by precision of R1 and R2

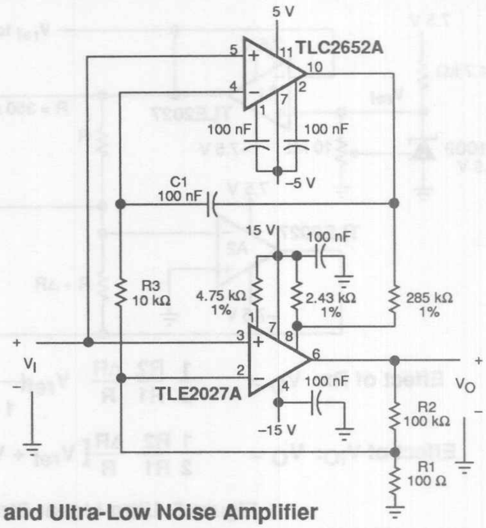


Figure 6. Ultra-Low Drift and Ultra-Low Noise Amplifier

Applications requiring extremely high dc precision combined with low noise can benefit from this composite amplifier.

The TLC2652A measures the dc error at the TLE2027A's input terminals and biases its offset pins to force the offset to within 1 µV. Similarly, the combined amplifier's offset drift with time and temperature is determined by the TLC2652A. The offset biasing at the TLE2027A is arranged so that the TLC2652A will always be able to find the servo point.

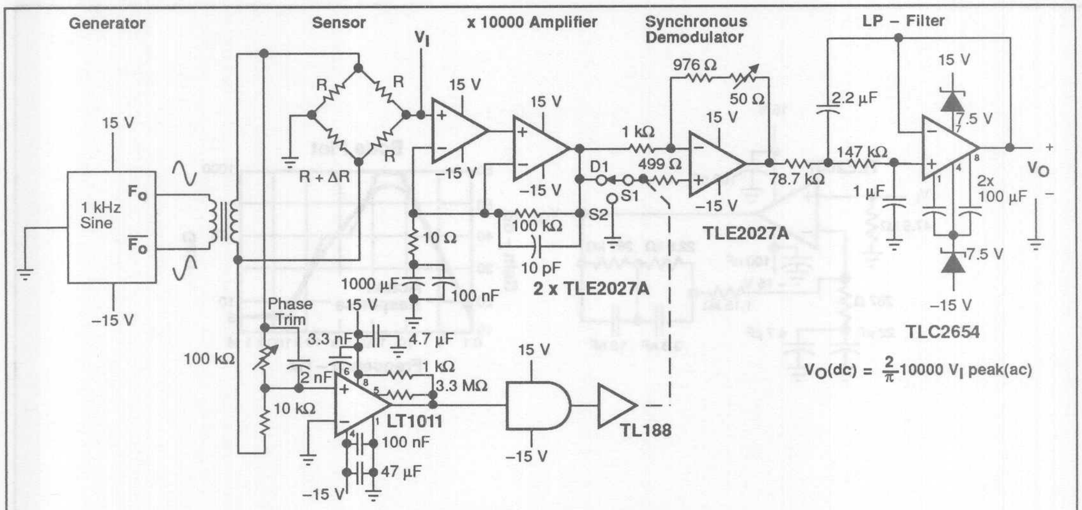
A 10-kΩ value for R3 minimizes the error caused by TLC2652A's input bias current and its drift. The 100-nF capacitor, C1, rolls off the TLC2652A at low frequencies ensuring that any ac signals do not affect the offset cancellation. The TLE2027A handles all ac frequency signals.

The noise of the composite amplifier is determined by the TLE2027A. Keeping R1 as low as 100 Ω reduces its thermal noise and eliminates the affect of input bias current noise from the TLE2027A.

If the amplifier is used for high frequency applications, an additional RC filter network at the noninverting input of the TLC2652A would prevent high frequency common mode signals from unbalancing its input stage, which could then cause changes in the offset voltage.

The settling time of the composite amplifier is affected by the dc correction loop and can limit its application for some high frequency circuits.

Lock-In Amplifier



$V_O(dc) = \frac{2}{\pi} 10000\ V_I$ peak(ac)

Figure 7. Lock-In Amplifier

Feeding a sensor bridge with an ac signal rather than a dc signal allows outputs from capacitive, inductive, and resistive sensors to be measured. Additionally, the sensitivity can be very high and is usually only limited by the thermal noise of the sensor, the noise of the high-gain-sensor amplifier, and the system bandwidth. When the signal frequency is constant, a very narrow bandpass filter following the high-gain amplifier can extract sensor signals buried in noise. A further signal rectification and averaging gives a dc output proportional to the sensor change. However, to build a narrow bandpass filter with, for instance, a 1-kHz-center frequency and a 1-Hz bandwidth requires precise components to ensure frequency accuracy and stability. Similarly, the sine-generator frequency must be accurate and stable.

This application shows one way to get over the frequency accuracy problem. The principle is still based on an ac carrier approach converting a change in sensor impedance to a dc voltage. The amplifier shown is followed by a synchronous demodulator that detects the amplified carrier modulated sensor signal. Because the desired signal information is contained within a carrier, the system constitutes an extremely narrow band-signal path. Non-carrier related components are rejected, and the amplifier passes only signals that are coherent with the carrier.

The very high gain (x 10000) ac amplifier is implemented by using a double TLE2027 amplifier block to achieve an impressive 160-dB open-loop gain at 1 kHz. The composite amplifier provides a typical 3-dB bandwidth of 150 kHz with an accurate closed-loop gain of 10000.

The zero-transition synchronized demodulator implemented by another TLE2027 shifts its gain between +1 and -1 in phase with the 1-kHz carrier. The "rectified" output signal is smoother with a 1-Hz active filter around the TLC2654 to provide a dc output (V_O) proportional to the sensor bridge output (V_S).

The dynamic range of the circuit is from 1 $\mu V_{p\text{-}p}$ to 1 $mV_{p\text{-}p}$ at V_S. With 20-$V_{p\text{-}p}$ across the bridge, the $\Delta R/R$ sensitivity of the system is able to measure a change in the sensor from one part in a million fairly accurately.

RIAA Phono Pre-Amp Circuit

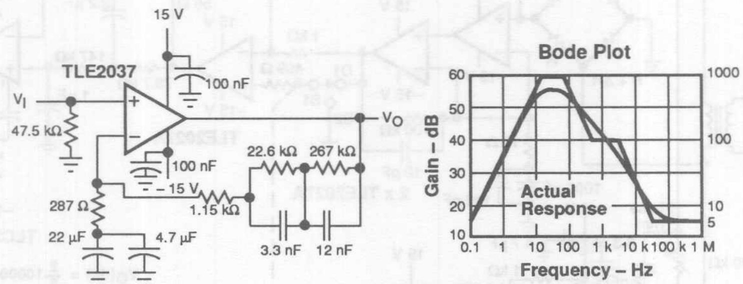


Figure 8. RIAA Phono Pre-Amp Circuit

A system requiring the ultimate in ac performance is audio high-fidelity CD players, with a dynamic range exceeding 90 dB, are pushing the performance of amplifiers to new levels.

Phonographic recording/replay is still the standard for many good quality hi-fi systems, and they require the ultimate in high-performance amplifiers. The TLE2037 with an open-loop gain of 153 dB, an offset of 25 μV and an 80-MHz gain-bandwidth product is an excellent choice in audio applications.

Record equalization circuits illustrate the importance of high gain and wide bandwidth in an ac application. The RIAA specification defines the characteristics of the phono replay preamplifier, and it takes into account the frequency response of magnetic pick-ups. The pre-amp must match and cancel out the pick-up's response. The result is roll-offs at 50 Hz and 2120 Hz with a zero at 500 Hz. The circuit incorporates a low-frequency pole and a corresponding zero at 20 Hz to remove rumble and low-frequency record effects.

For a gain of 1000, the op amp needs a large gain-bandwidth product to remove any gain error. The chosen op amp, the TLE2037, has a loop-gain in excess of 40 dB at 20 kHz. Also note that the device is still operating well within its full power bandwidth.

To achieve these levels of performance the op amp has been decompensated, which means that the compensation capacitance has been reduced to allow faster slew rates and higher bandwidth. However, the decompensated op amp will only remain stable for closed-loop gains of greater than five. Therefore, the high frequency gain of the circuit has been designed to flatten out with a gain of 5; this flattening occurs at 40 kHz.

The types of components used must also be considered. The circuit has been configured so as not to require the use of noisy, low-performance electrolytic capacitors. Polypropylene capacitors with their very low tan δ give good performance. For the lowest frequency zero, a polycarbonate capacitor has been used.

The resistors used are all metal film for high precision and low flicker noise. They are readily available in E96 series values, providing an inexpensive and accurate solution to the pre-amp's requirements.

Conclusion

Our intention is that your time will be well-spent traversing this manual. The TLE2027/37 are significant advances in the world of high performance operational amplifiers not only in the parametric sense, but in the functional, user-friendly sense. As seen in several of the application circuits, the TLE2027/37 can be applied in many functions whether for improving high-accuracy instruments, or adding more quality to reproduced music.

With new technology and memory-jogging design considerations and applications, add your unique quality of innovations, and the future is bright for the next generation of equipment and systems.

Call the applications phone number listed on the inside of the front cover with any product or applications hints that you would care to share.

Acknowledgments

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